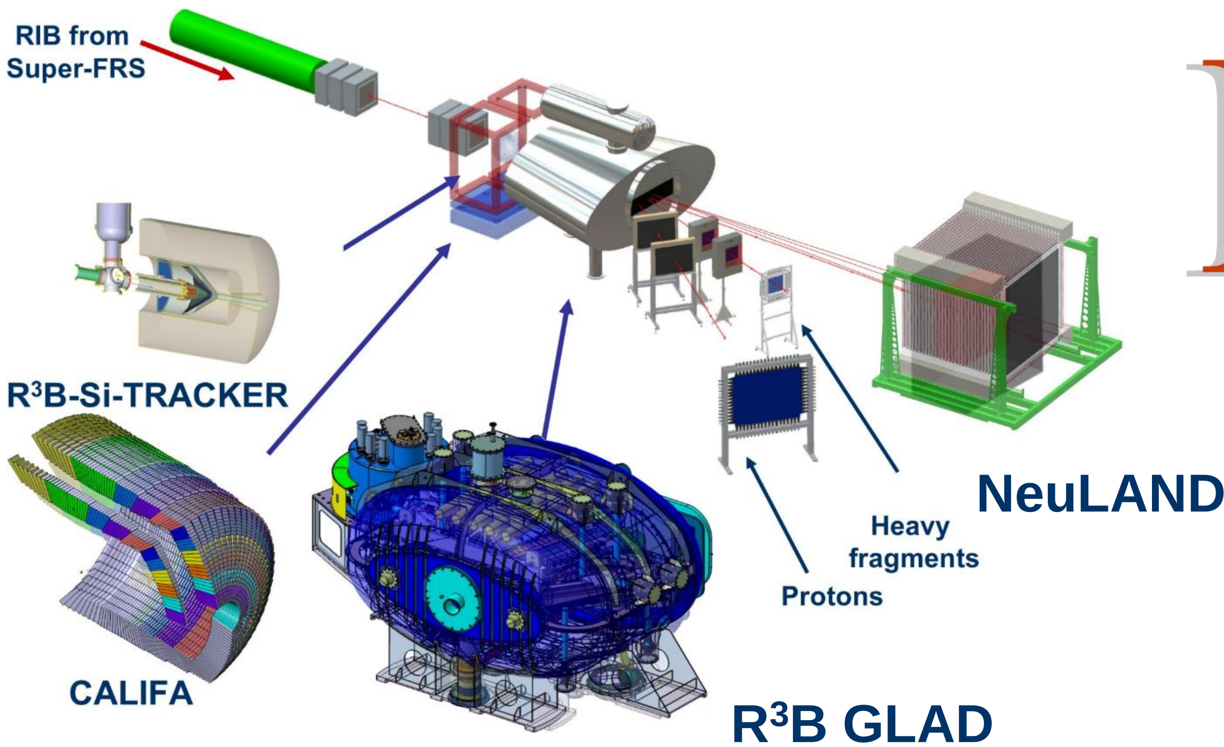
Dipole response and constraints on the nuclear equation of state

Dominic Rossi



Outline

TECHNISCHE UNIVERSITÄT DARMSTADT

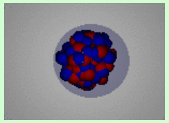
- Introduction
  - What is the Equation of State of nuclear matter?
  - Why measure low-lying E1 strength?
  - Why measure it in ^{68}Ni?
- Experimental method:
  - Measuring E1 strength in unstable nuclei
  - R^{3}B-LAND setup at GSI
- Results
  - E1 strength in ^{68}Ni
  - Dipole polarizability
  - Neutron-skin thickness of ^{68}Ni and ^{208}Pb
- Outlook
- Summary

R3B

Why measure low-lying E1 strength?

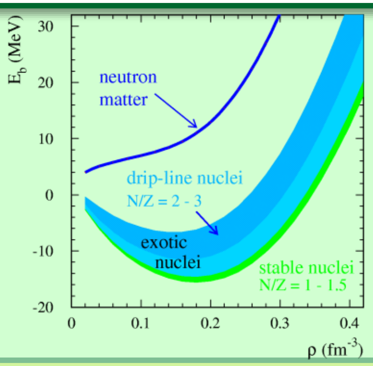
Low-lying E1 strength

Dipole polarizability

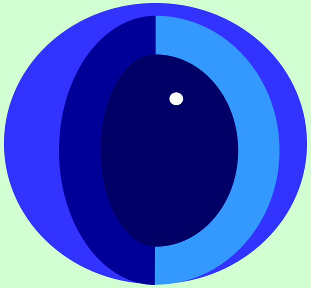


$$\alpha_D = \frac{\hbar c}{2\pi^2} \int_0^\infty \omega^{-2} \sigma_\gamma(\omega) d\omega$$

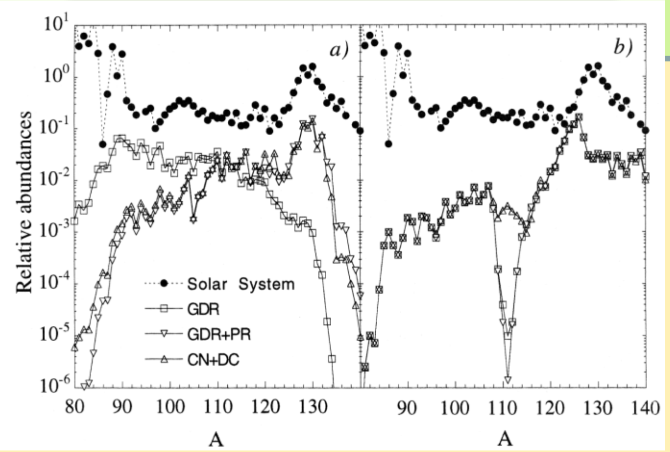
Equation of State



Neutron skin

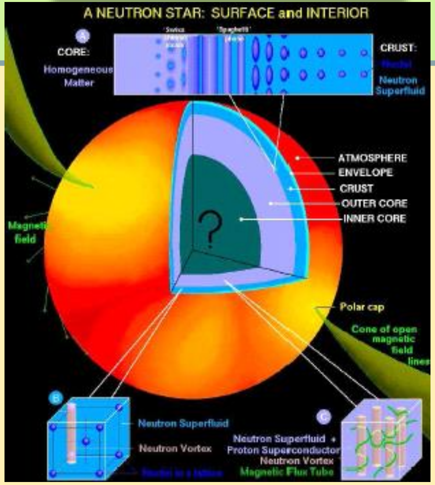


Nucleosynthesis



S. Goriely, Phys. Lett. B **436**(1-2), 10-18 (1998)

Neutron star



Nuclear Equation of State: basics

- At the beginning: liquid-drop formula (Bethe and Weizsäcker)

$$\boxed{B(Z,N) = a_V A - a_S A^{2/3} - a_C \frac{Z^2}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \cdots}$$

- Then, one defines the binding energy per nucleon (in the thermodynamic limit)

$$\boxed{\varepsilon(\alpha) = -\frac{B(Z,N)}{A} = -a_V + a_A \frac{(N-Z)^2}{A^2} = -a_V + J\alpha^2}$$

- Nuclear matter is not incompressible ➔ density dependence ➔ $\varepsilon(\alpha) \to E(\rho,\alpha)$

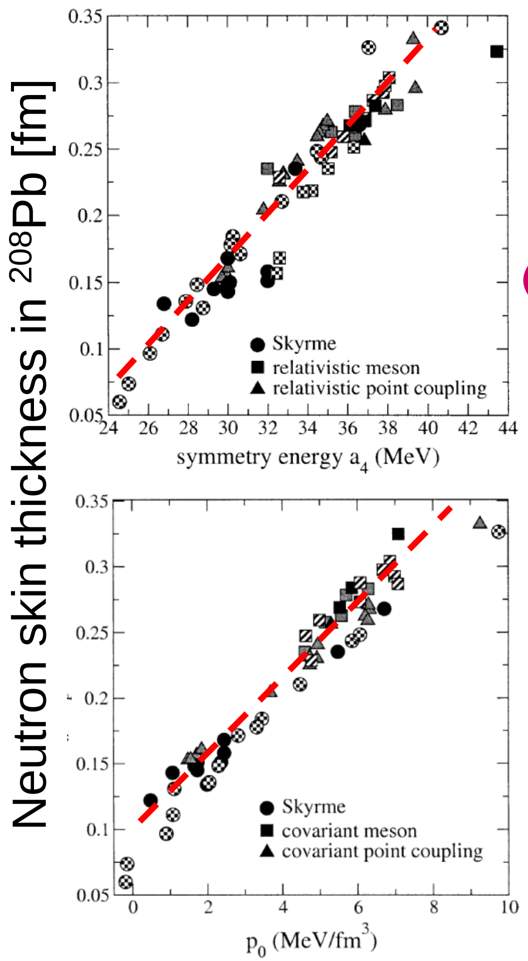
$$\boxed{E(\rho,\alpha) = E(\rho,0) + S_2(\rho)\alpha^2 + \cdots}$$

- This is a possible expression of the Equation of State of nuclear matter

C. Horowitz, *et al.*, JPG 41, 093001 (2014)

Nuclear Equation of State: symmetry energy

TECHNISCHE UNIVERSITÄT DARMSTADT



R.J. Furnstahl, NPA **706**, 85-110 (2002)

$$E(\rho,\alpha)=E(\rho,0)+S_2(\rho)\alpha^2+O(\alpha^4)\,,\ \alpha=\frac{N-Z}{A}$$

$$E(\rho,0)=-a_V+\frac{K_0}{18\rho_0^2}(\rho-\rho_0)^2+\dots$$

$$S_2(\rho)=\frac{1}{2}\frac{\partial^2E(\rho,\alpha)}{\partial\alpha^2}\Big|_{\alpha=0}=$$

$$=a_4+\frac{p_0}{\rho_0^2}(\rho-\rho_0)+\frac{\Delta K_0}{18\rho_0^2}(\rho-\rho_0)^2+\dots$$

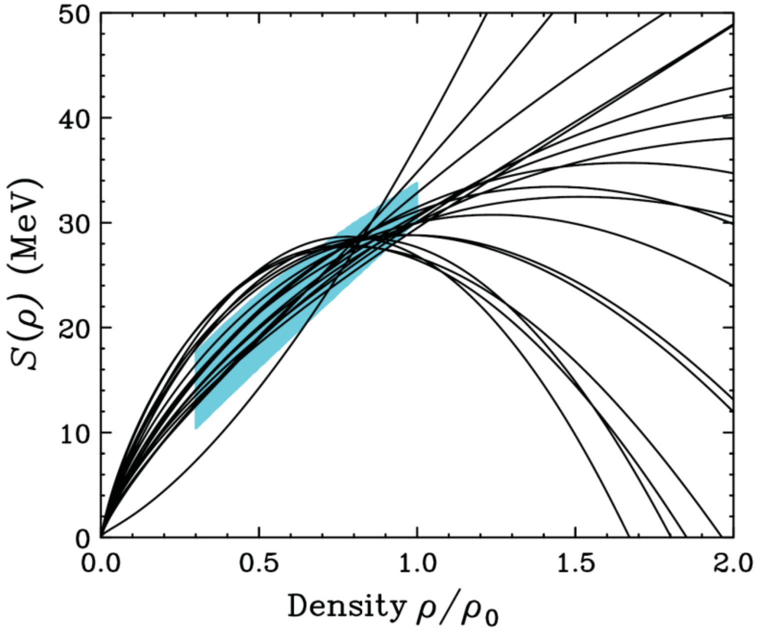
a_4 ➔ J

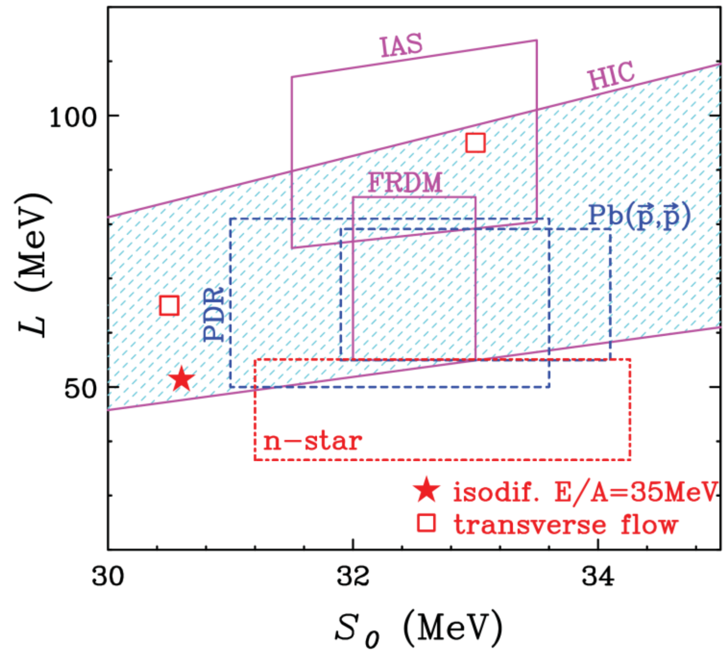
p_0 ➔ $S'(\rho)|_{\rho=\rho_0}=\dfrac{L}{3\rho_0}$

- a_4: symmetry energy
- p_0: symmetry energy pressure ➔ density dependence
- Linear correlation between neutron skin thickness and a_4 and p_0 parameters of nuclear Equation of State for various mean-field models for ^{208}Pb case

R3B

Nuclear Equation of State: symmetry energy

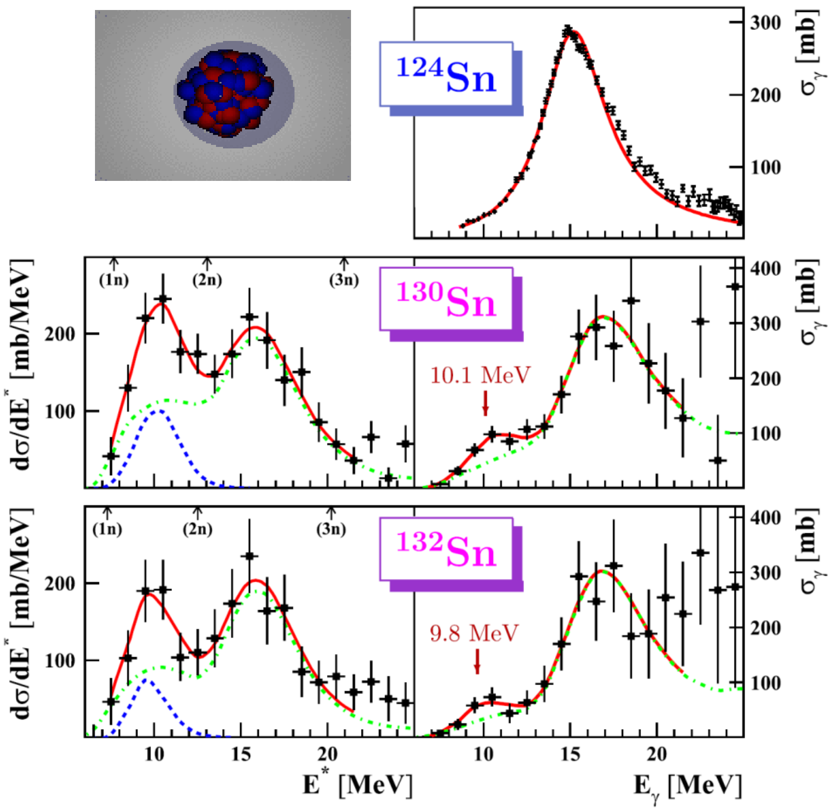




- Density dependence of the symmetry energy is not well constrained
- Experimental data is necessary to provide constraints as tight as possible
- Results from various types of probing of nuclear matter are combined to provide best possible set of constraints

M.B. Tsang, *et al.*, PRC 86, 015803 (2012)

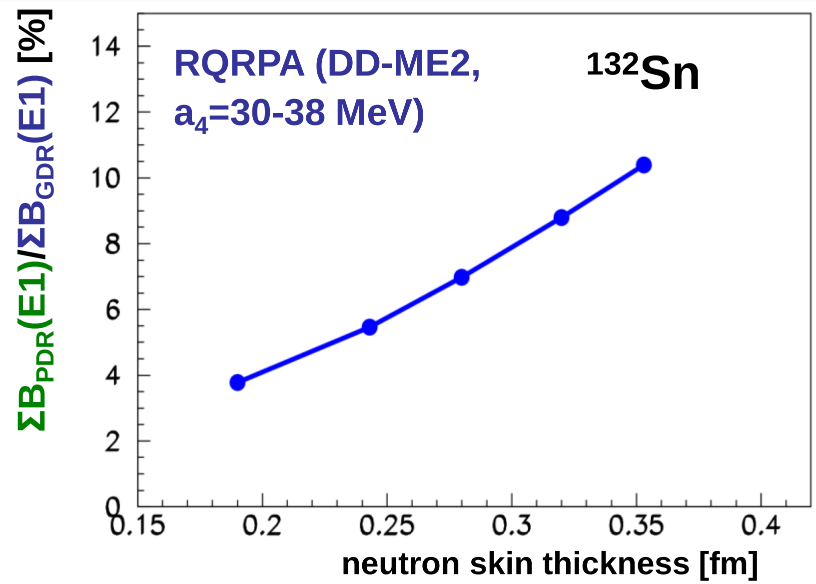
Measuring $\Delta R_{n,p}$ using low-lying E1 strength



P. Adrich *et al.*, PRL **95**, 132501 (2005)

GDR ➔ Breit-Wigner
PDR ➔ Gaussian

- RQRPA calculations provide correlation between the measured PDR strength and the neutron skin thickness



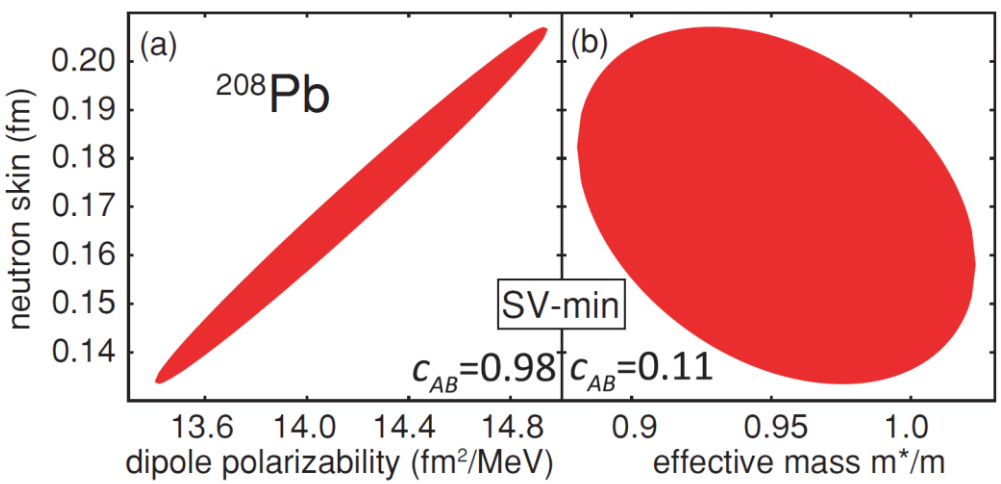
- Requires assumption of a specific line-shape of PDR and GDR
- Photoabsorption c.s. not very sensitive to low-lying E1 strength

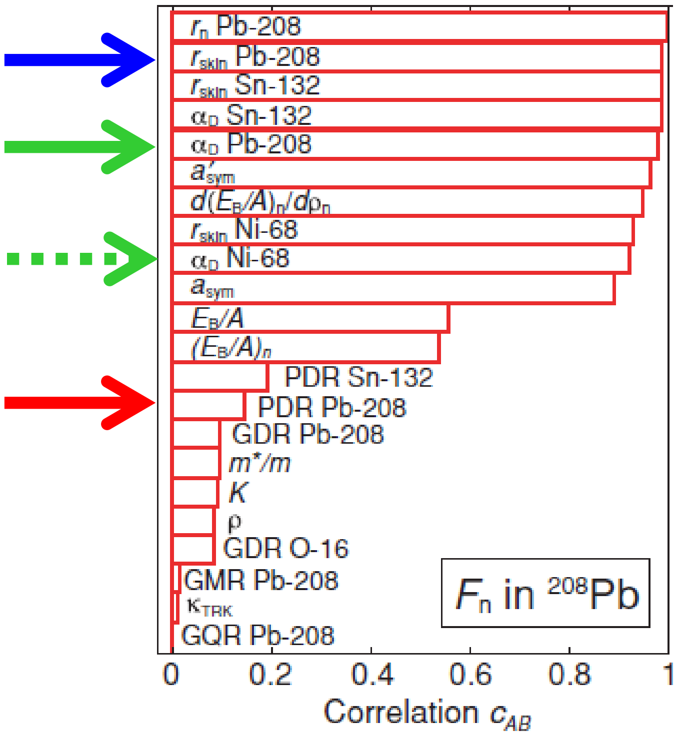
Selecting a better observable for $\Delta R_{n,p}$

PHYSICAL REVIEW C **81**, 051303(R) (2010)

Information content of a new observable: The case of the nuclear neutron skin

P.-G. Reinhard[1] and W. Nazarewicz[2,3,4,5]



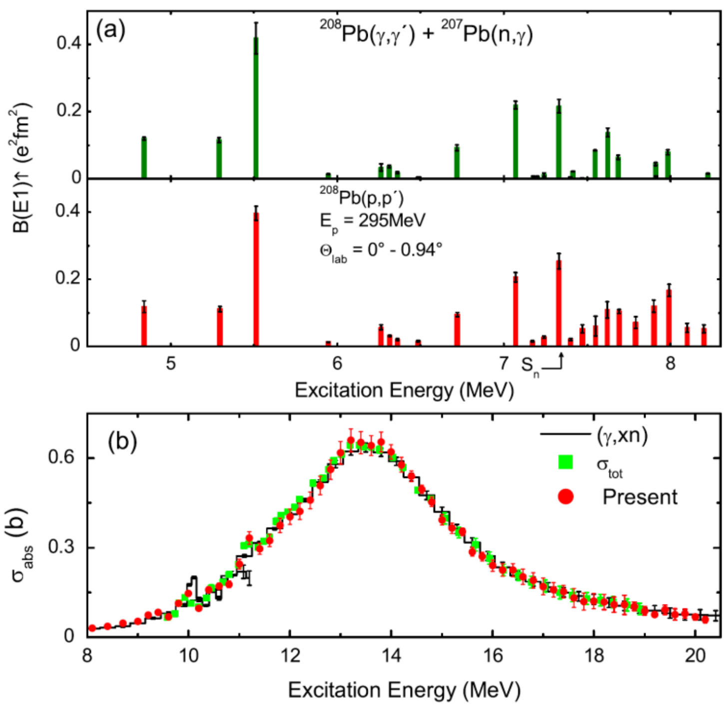


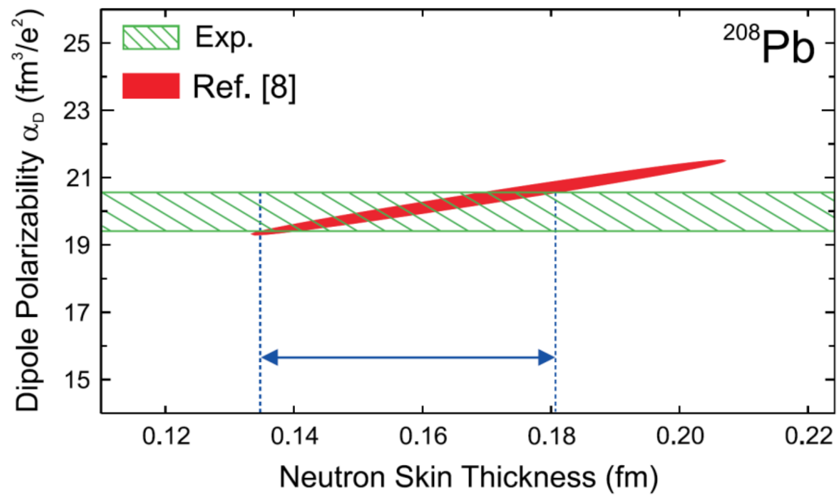
Dipole polarizability of ^{208}Pb

PRL **107,** 062502 (2011) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2011

Complete Electric Dipole Response and the Neutron Skin in ^{208}Pb

A. Tamii,[1] I. Poltoratska,[2] P. von Neumann-Cosel,[2,*] Y. Fujita,[3] T. Adachi,[3,4] C. A. Bertulani,[5] J. Carter,[6] M. Dozono,[7] H. Fujita,[1] K. Fujita,[7] K. Hatanaka,[1] D. Ishikawa,[1] M. Itoh,[8] T. Kawabata,[9] Y. Kalmykov,[2] A. M. Krumbholz,[2] E. Litvinova,[10,11] H. Matsubara,[12] K. Nakanishi,[12] R. Neveling,[13] H. Okamura,[1] H. J. Ong,[1] B. Özel-Tashenov,[10] V. Yu. Ponomarev,[2] A. Richter,[2,14] B. Rubio,[15] H. Sakaguchi,[1] Y. Sakemi,[8] Y. Sasamoto,[12] Y. Shimbara,[3,16] Y. Shimizu,[17] F. D. Smit,[13] T. Suzuki,[1] Y. Tameshige,[18] J. Wambach,[2] R. Yamada,[16] M. Yosoi,[1] and J. Zenihiro[1]

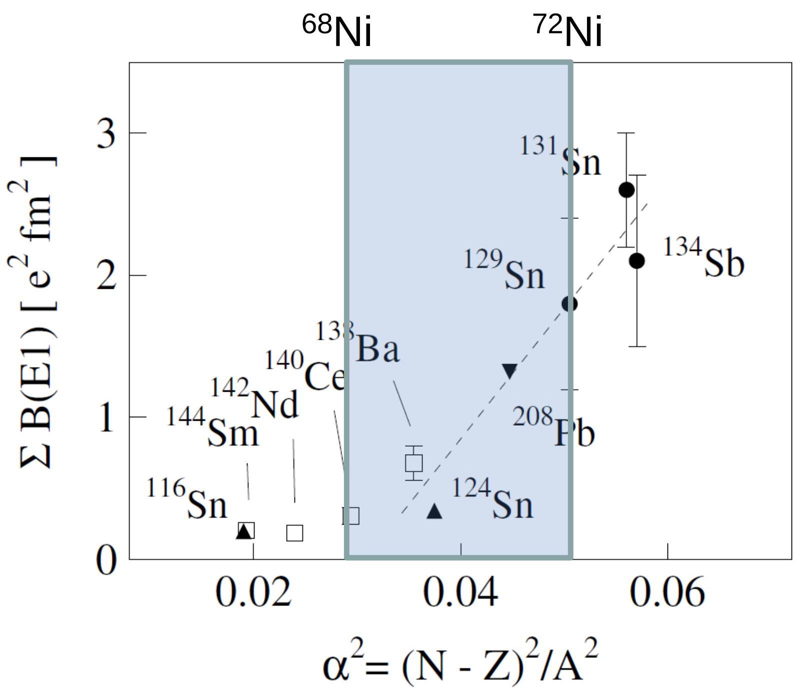




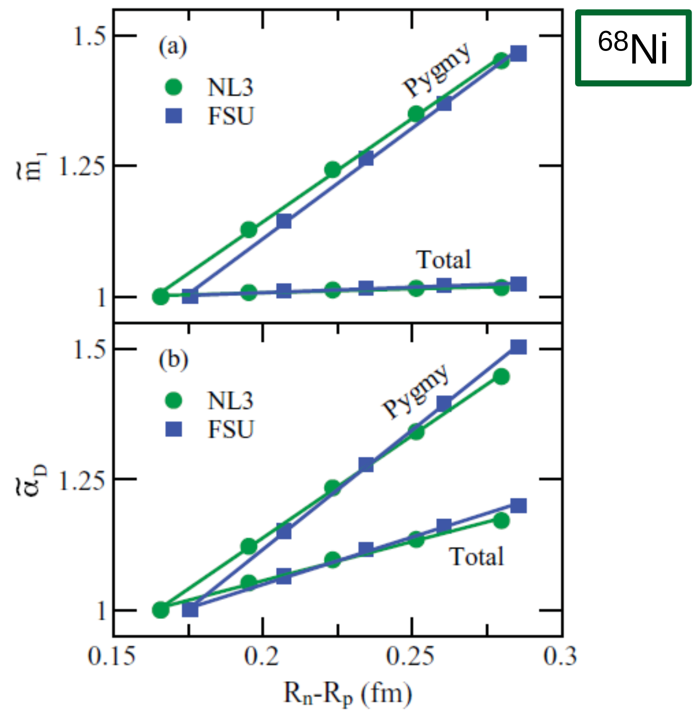
Measured α_D up to 20 MeV: 18.9(13) fm^3/e^2
Extrapolated value up to 130 MeV: 20.1(6) fm^3/e^2
➔ $r_{\text{skin}} = 0.156^{+0.025}_{-0.021}$ fm

Why measure dipole polarizability in ^{68}Ni?

- Cover large asymmetry window within given mass range
- Larger sensitivity of $\Delta R_{n,p}$ on α_D than in ^{208}Pb
- Measurement of evolution of E1 strength within isotopic chain → isospin dependence



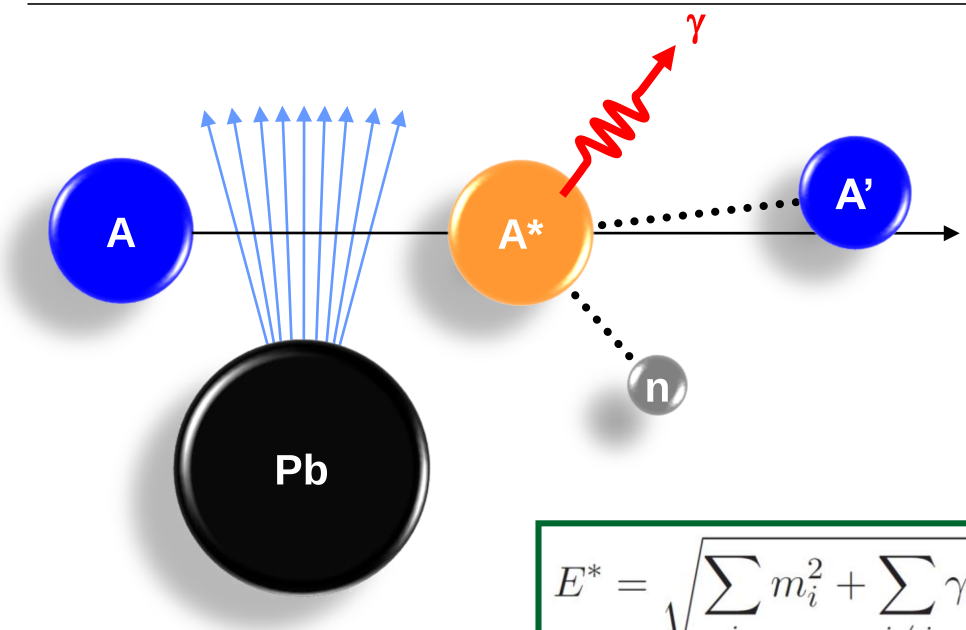
A. Klimkiewicz *et al.*, PRC **76**, 051603(R) (2007)

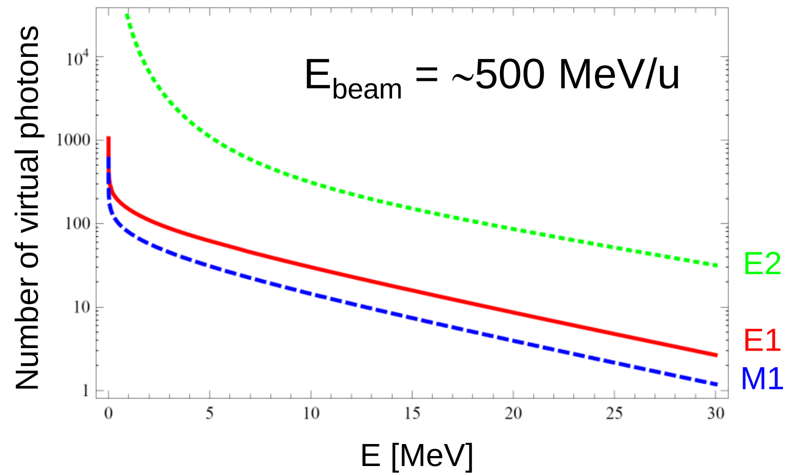


J. Piekarewicz, PRC 83, 034319 (2011)

Measuring E1 strength in unstable nuclei

TECHNISCHE UNIVERSITÄT DARMSTADT





$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j \left(1 - \beta_i \beta_j \cos\vartheta_{ij}\right)} + E_\gamma - m_{proj}$$

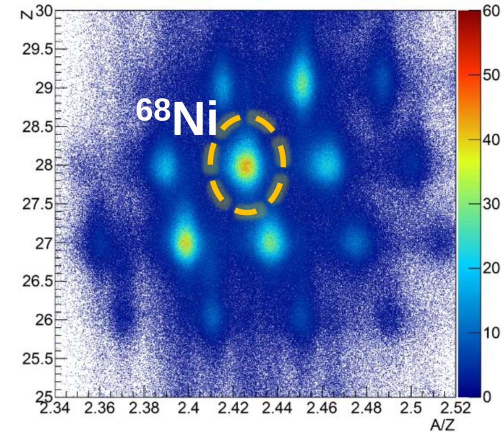
- Short lifetime of projectile ➔ requires experiment in **inverse kinematics**
- Heavy-ion-induced **electromagnetic excitation**, *via* the virtual photon approach
- Reconstruction of excitation energy (using invariant mass) of each event requires detection of **ALL** participating species (identification and momentum):

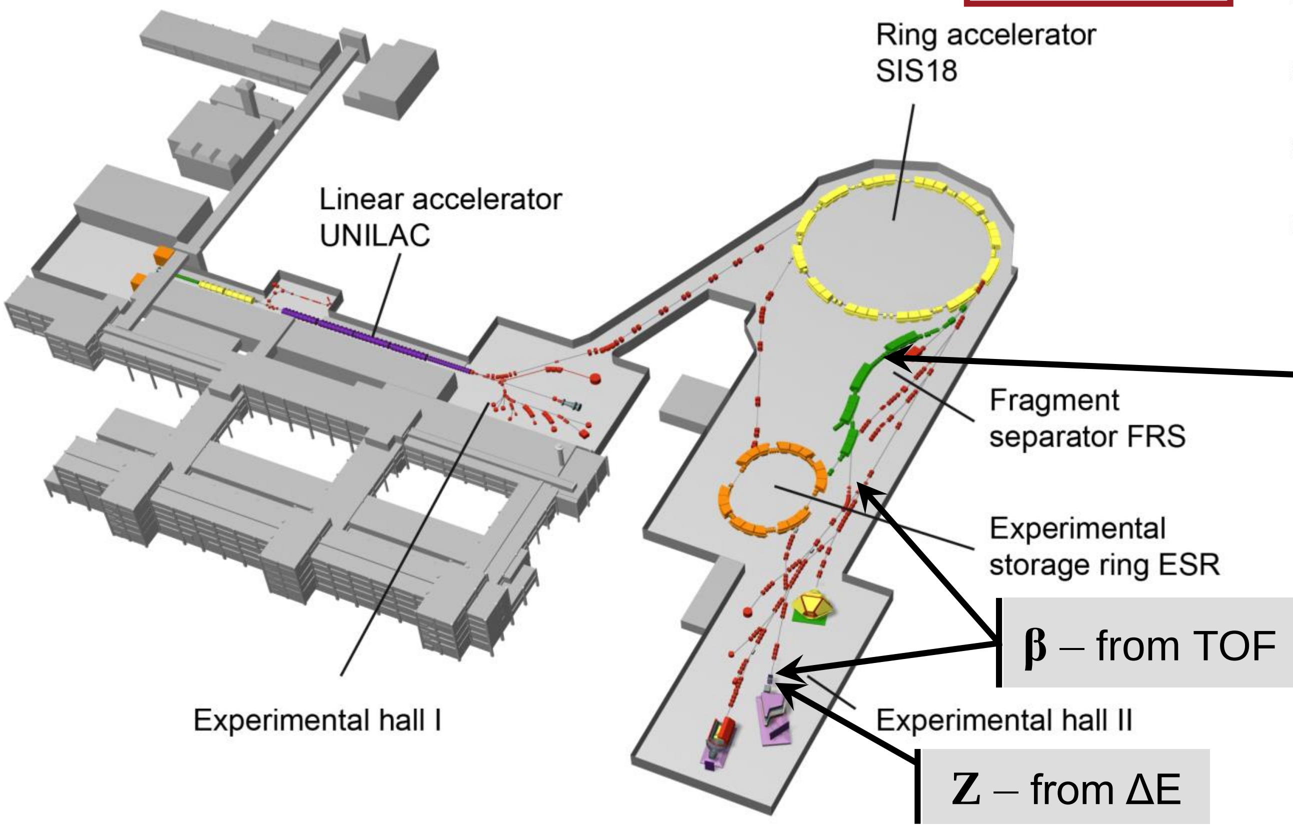
  ➔ Requires high-efficiency and high-resolution neutron and gamma detectors (for n-rich nuclei)

R3B

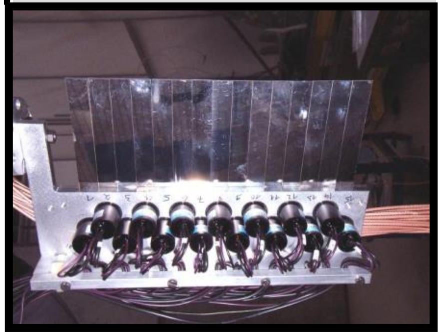
GSI experimental facility

$$\frac{\mathbf{A}}{\mathbf{Z}} = \frac{e}{m_u c}\frac{\mathrm{B}\rho}{\beta\gamma}$$



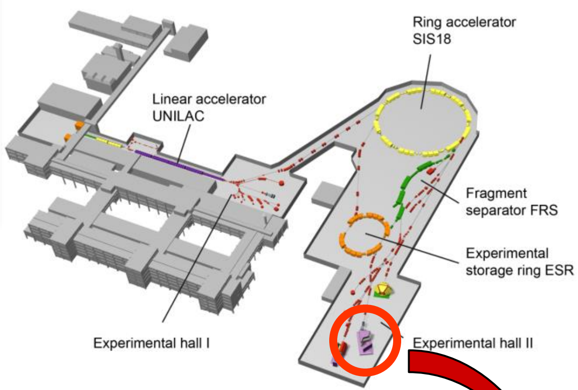


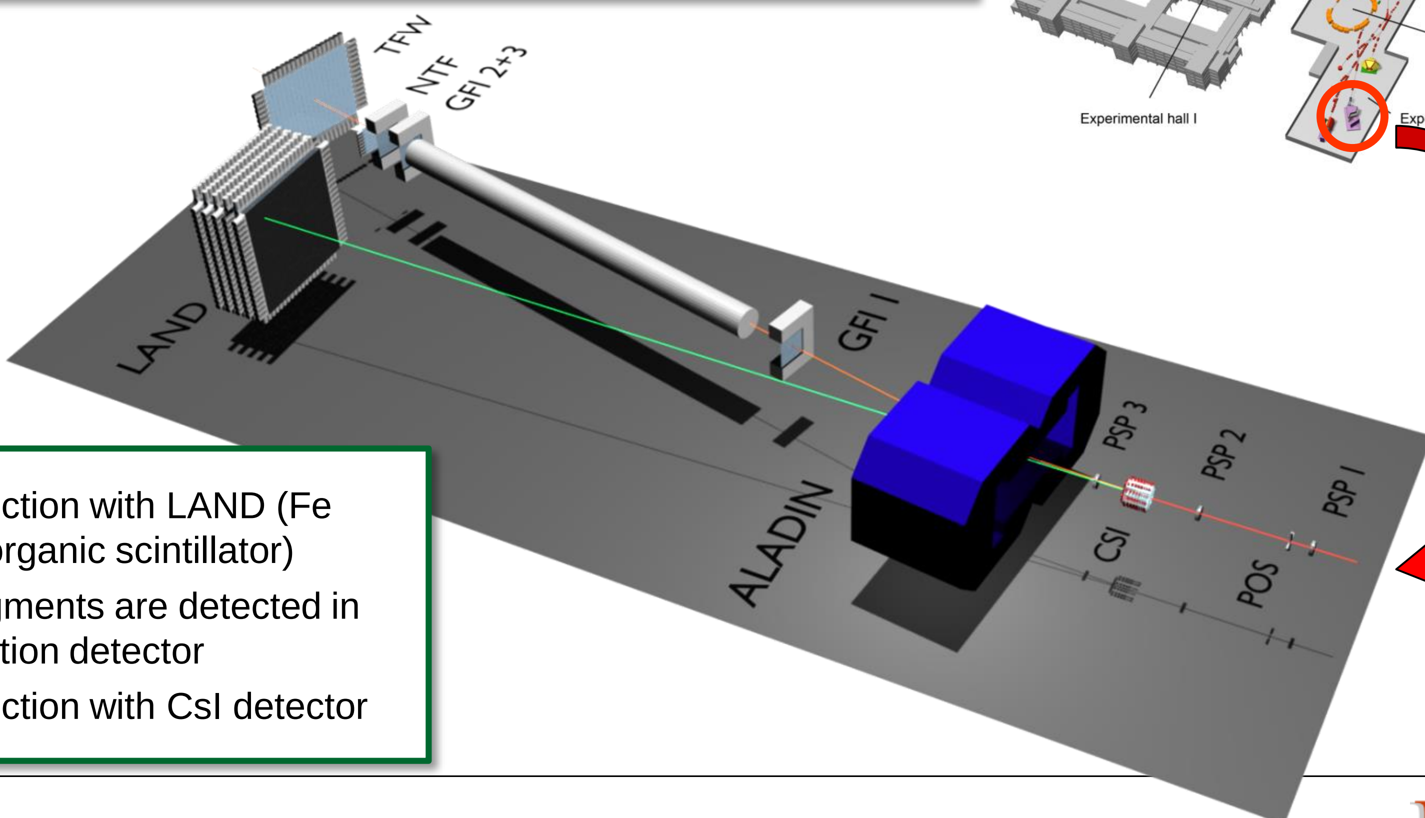
Bρ – from position at middle focal plane of the FRS



R³B-LAND setup

- Kinematic forward-focusing (relativistic beam energies)
  → high-acceptance measurement (almost full solid angle covered)
- Beam tracking in Cave C: Si detectors (PSP) and scintillation detectors (POS, GFI, TFW)

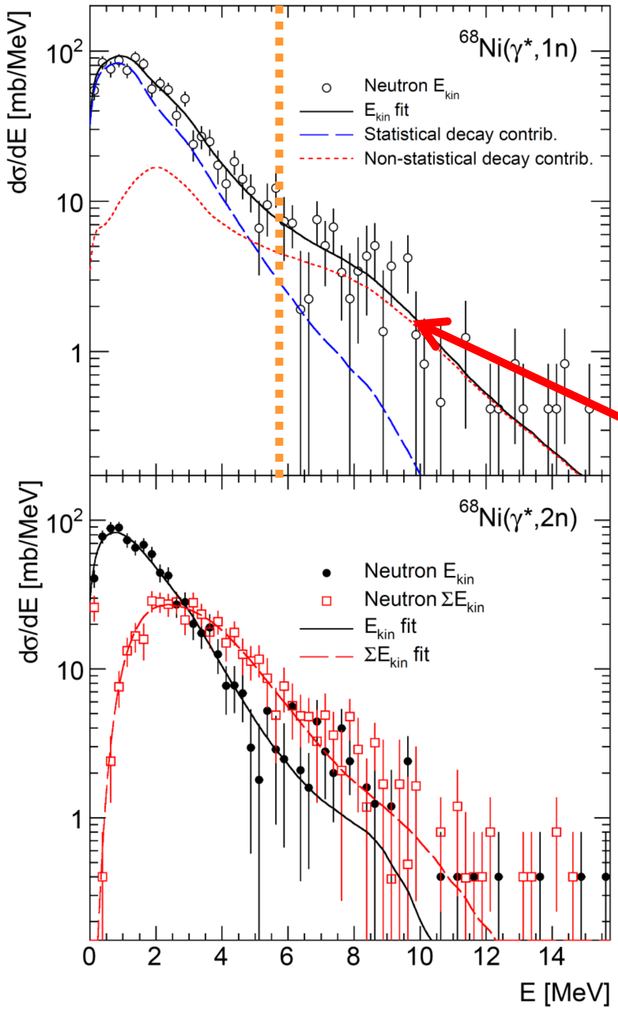




- Neutron detection with LAND (Fe converter + organic scintillator)
- Charged fragments are detected in TFW scintillation detector
- Gamma detection with CsI detector

Reconstructing E*: neutrons

TECHNISCHE UNIVERSITÄT DARMSTADT

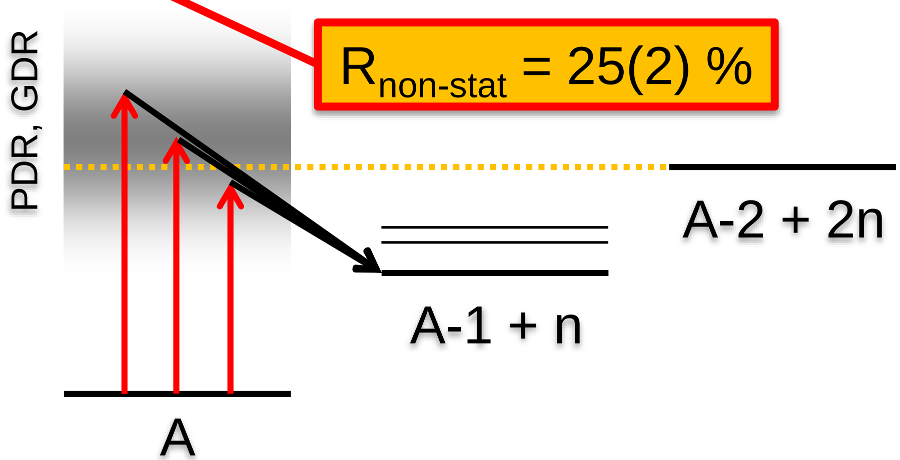


- Neutron kinetic energies reach well beyond the 2n threshold (dotted orange line)

→ Not expected with statistical decay

- Only decay to the vicinity of the A-1 ground state was considered
- Non-statistical decay branching ratio obtained from fit to neutron energies

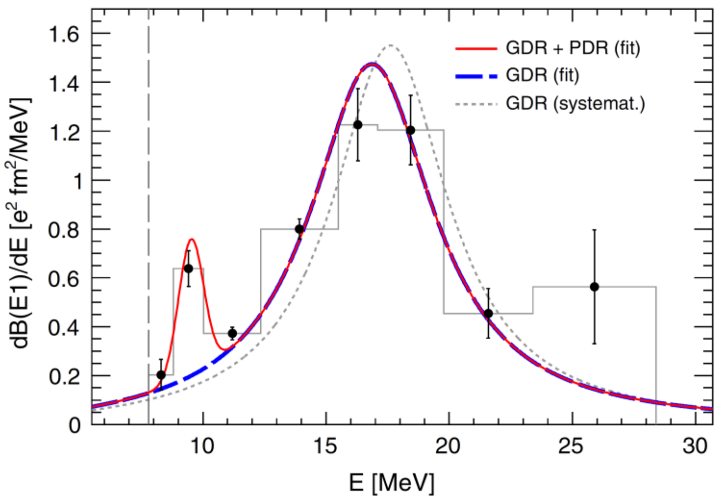
$R_{non\text{-}stat}$ = 25(2) %



R3B

Low-lying E1 strength in ^{68}Ni

TECHNISCHE UNIVERSITÄT DARMSTADT



PRL **111,** 242503 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

Measurement of the Dipole Polarizability of the Unstable Neutron-Rich Nucleus ^{68}Ni

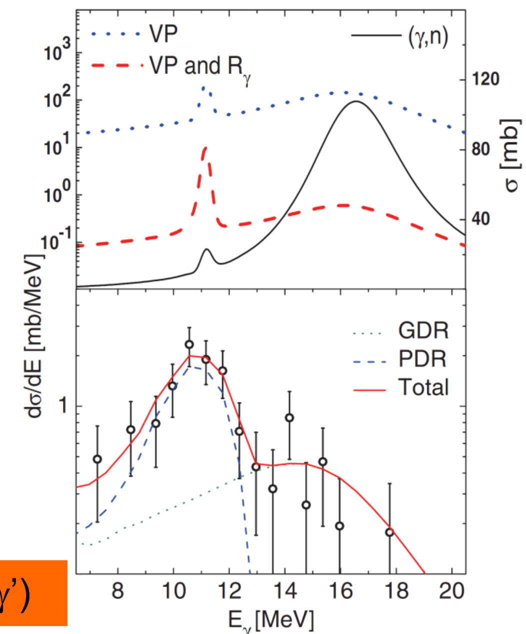
D.M. Rossi, *et al*.

^{68}Ni (γ^*,xn)

PRL **102,** 092502 (2009) PHYSICAL REVIEW LETTERS week ending 6 MARCH 2009

Search for the Pygmy Dipole Resonance in ^{68}Ni at 600 MeV/nucleon

O. Wieland, *et al*.



^{68}Ni (γ^*,γ')

- One-step GDR+PDR fit to „deconvoluted“ data
- Comparison of fit result with RISING data

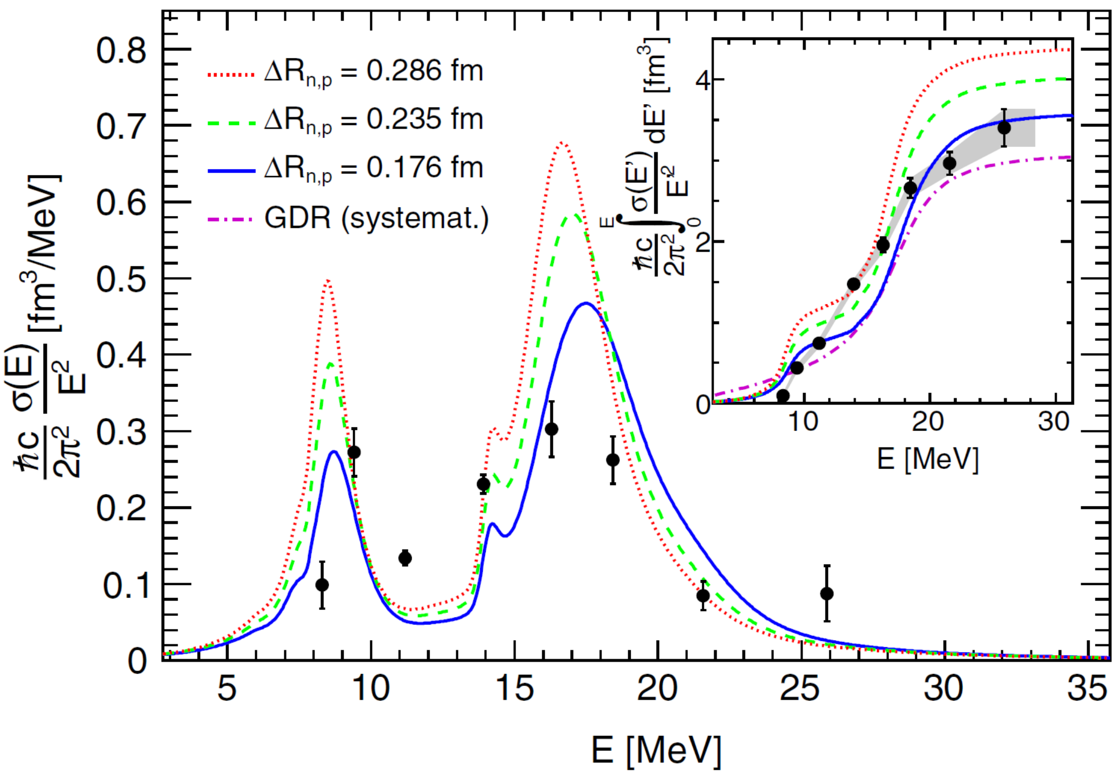
PDR in ^{68}Ni	(γ^*,xn)	(γ^*,γ')
E_m [MeV]	9.55(17)	11.0(5)
σ [MeV]	0.51(13)	< 1
S_{TRK} [%]	2.8(5)	-

$$\frac{d\sigma_{E1}}{dE_\gamma} = \sigma^{exc} * R_\gamma = \left(\frac{1}{E_\gamma} N \sigma^{abs}\right) * R_\gamma$$

R_γ (PDR) ≈ 4 % ➔ S_{TRK} ≈ 5 %

R3B

Dipole polarizability in ^{68}Ni



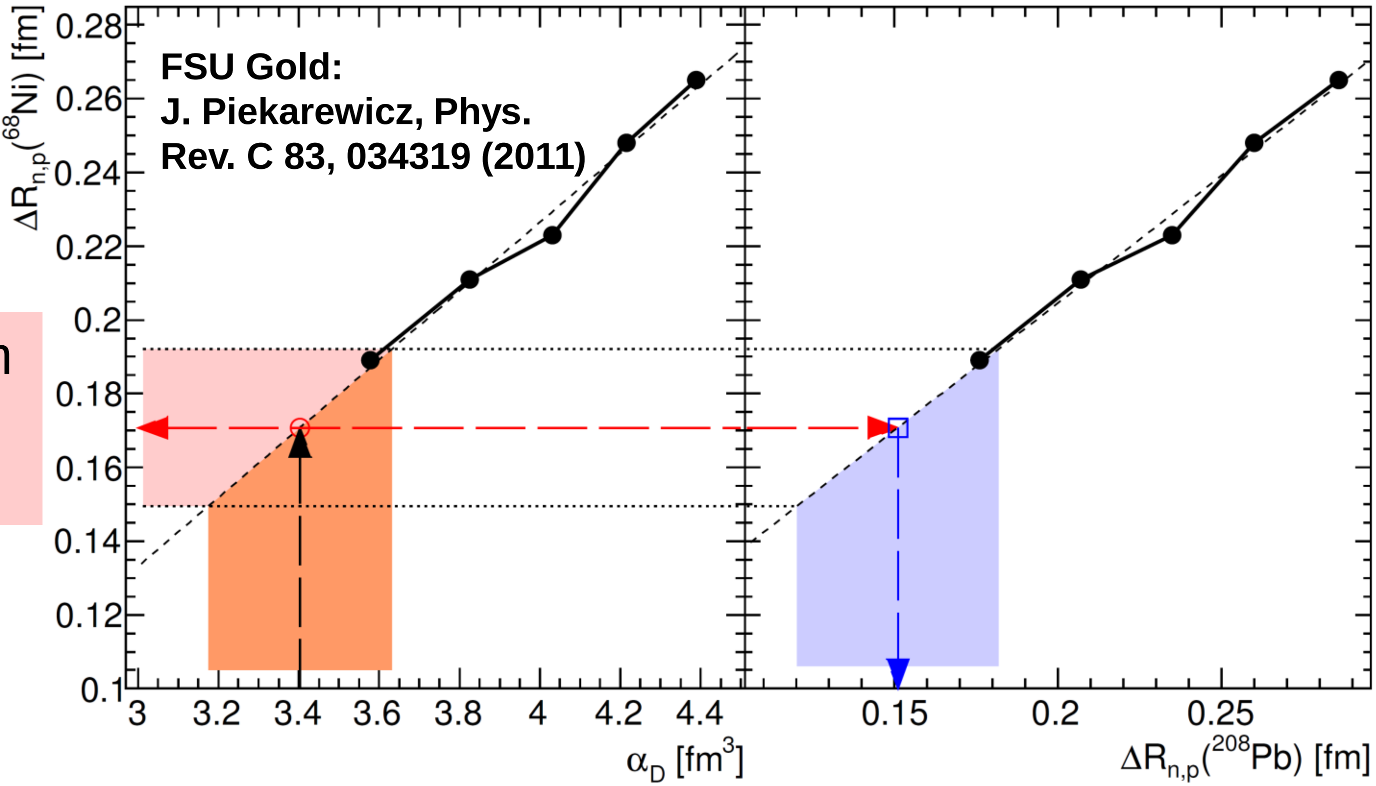
D.M. Rossi, *et al.*, PRL 111, 242503 (2013)

- Extraction of dipole polarizability from inverse energy-weighted dipole response
- Experimental data compared to FSUGold RMF calculations (Piekarewicz, PRC 83, 034319 (2011)), as well as GDR alone

➔ Significant enhancement when compared to GDR

- Theory "adjusted" to account for experimental integration limits (7.792 to 28.4 MeV) and resolution (→ Gaussian smearing)

Neutron-skin thickness of ^{68}Ni



$\Delta R_{n,p}$ = 0.17(2) fm
in ^{68}Ni
from exp.

$\Delta R_{n,p}$ = 0.15(3) fm
in ^{208}Pb
from same parametrization

Agrees with (p,p') measurement on ^{208}Pb (Tamii *et al.*)

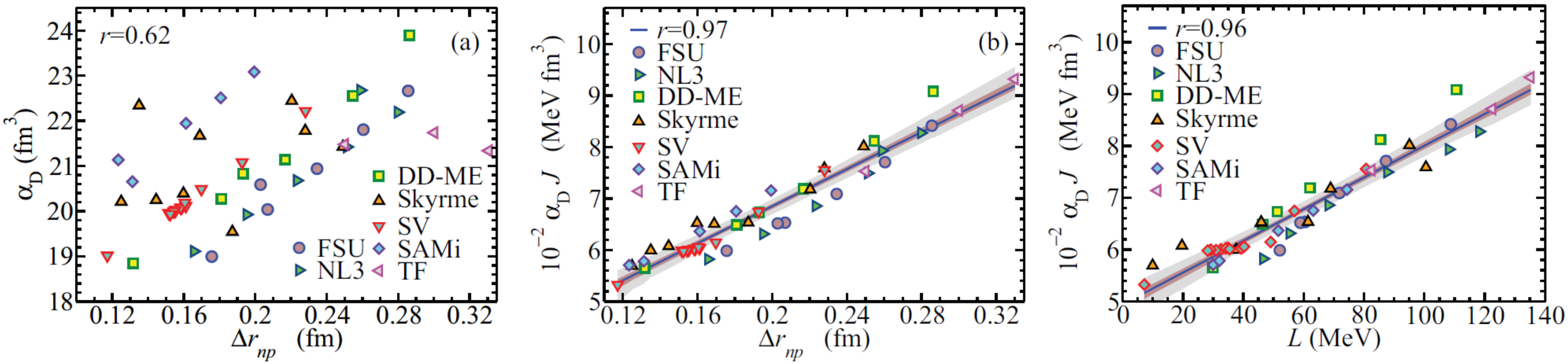
$r_{\text{skin}} = 0.156^{+0.025}_{-0.021}$ fm

Strategy to extract EOS parameters

TECHNISCHE UNIVERSITÄT DARMSTADT

^{208}Pb

$$\alpha_D^{DM} \approx \frac{\pi e^2}{54}\frac{A\langle r^2\rangle}{J}\left[1+\frac{5}{2}\frac{\Delta r_{np}^{DM}}{I\langle r^2\rangle^{1/2}}\right]$$

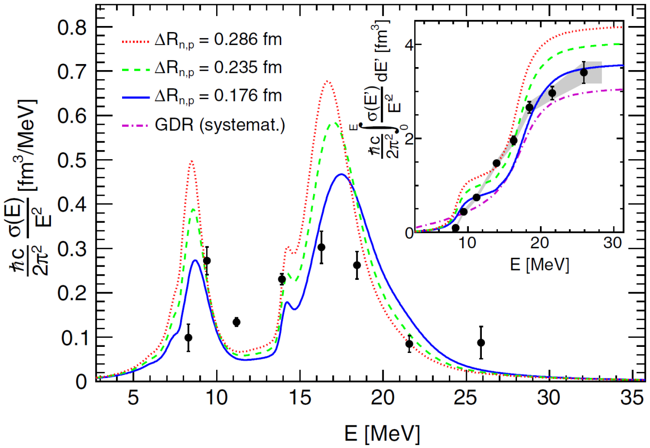


X. Roca-Maza, *et al.*, PRC 88, 024316 (2013)

- Stronger linear correlation between models when α_D*J is used instead of α_D
- Possibility to extract EOS parameters using various models

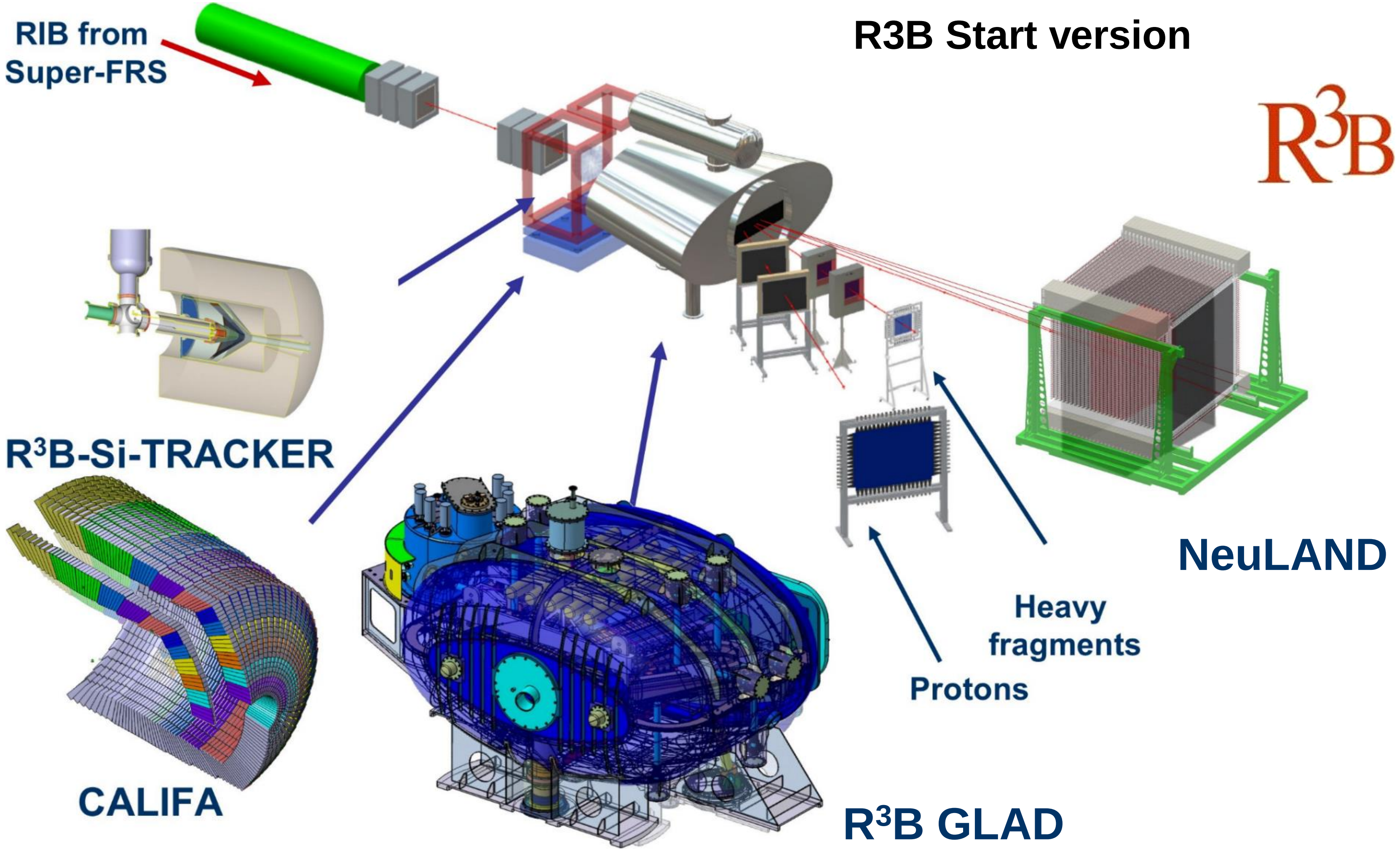
R^{3}B

Outlook: determine full α_D for ^{68}Ni

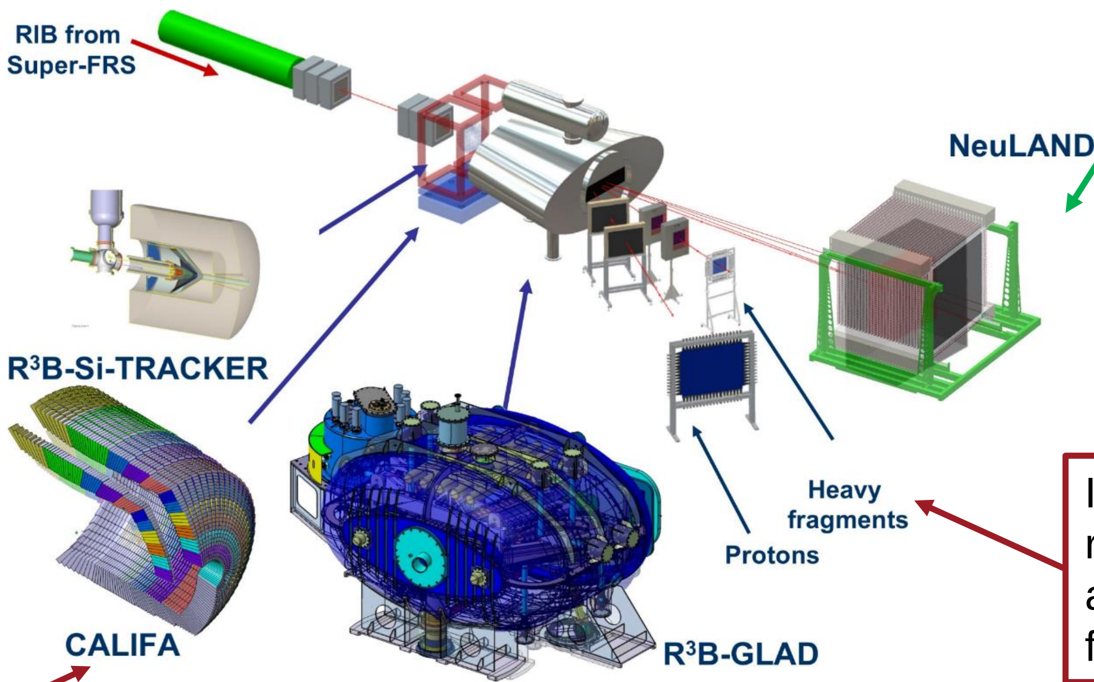


- Expand integration range from 7.792-28.4 MeV to 0-140 MeV
- Use Breit-Wigner tails from fit to data to extrapolate E1 strength beyond measurement range
- Reflect extrapolation in total error

Future setup: R³B



Future setup: R³B



Higher multi-neutron detection efficiency (63% for 4n at 1 GeV); better resolution ($\Delta p/p \approx 10^{-3}$)

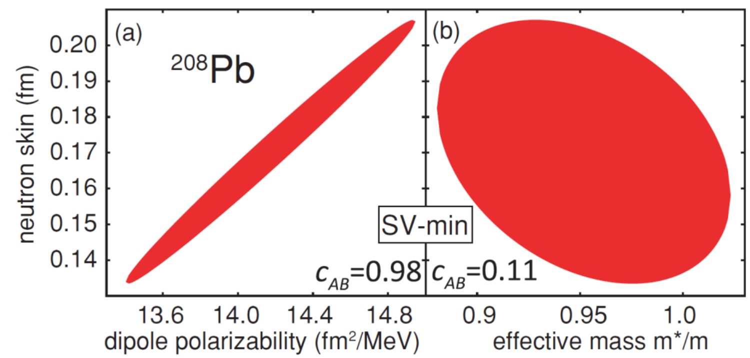
Improved $\sigma_{\Delta E}$ and σ_t, resulting in a better Z and A identification of fragments

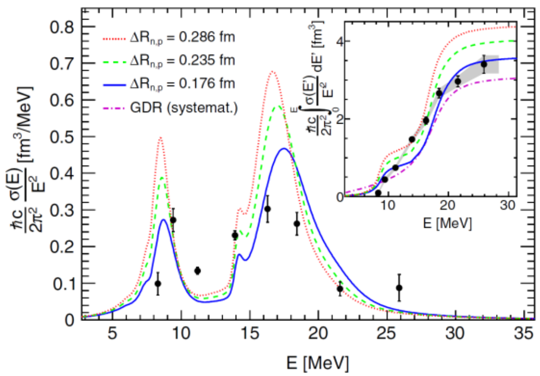
Highest possible calorimetric efficiency required

Allows for beams up to 15 Tm (bending of 18°) already in Cave C (*e.g.*, ~1.1 GeV/u ^{68}Ni!)

Summary

- Use of dipole polarizability instead of E1 strength to extract EOS parameters due to better parameter correlations





- Dipole polarizability of ^{68}Ni was measured successfully
- Neutron-skin thicknesses of ^{68}Ni and ^{208}Pb in good agreement

- Ongoing work:
  - Full dipole polarizability of ^{68}Ni → extraction of EOS parameters
  - Dipole polarizabilities of $^{70-72}$Ni
  - Analysis of n-rich Sn isotopes (on both sides of neutron threshold)

Collaboration

TECHNISCHE UNIVERSITÄT DARMSTADT

PRL **111,** 242503 (2013) PHYSICAL REVIEW LETTERS week ending 13 DECEMBER 2013

Measurement of the Dipole Polarizability of the Unstable Neutron-Rich Nucleus ^{68}Ni

D. M. Rossi,[1,2,*] P. Adrich,[1] F. Aksouh,[1,†] H. Alvarez-Pol,[3] T. Aumann,[4,1,‡] J. Benlliure,[3] M. Böhmer,[5] K. Boretzky,[1] E. Casarejos,[6] M. Chartier,[7] A. Chatillon,[1] D. Cortina-Gil,[3] U. Datta Pramanik,[8] H. Emling,[1] O. Ershova,[9] B. Fernandez-Dominguez,[3,7] H. Geissel,[1] M. Gorska,[1] M. Heil,[1] H. T. Johansson,[10,1] A. Junghans,[11] A. Kelic-Heil,[1] O. Kiselev,[1,2] A. Klimkiewicz,[1,12] J. V. Kratz,[2] R. Krücken,[5] N. Kurz,[1] M. Labiche,[13,14] T. Le Bleis,[1,9,15] R. Lemmon,[14] Yu. A. Litvinov,[1] K. Mahata,[1,16] P. Maierbeck,[5] A. Movsesyan,[4] T. Nilsson,[10] C. Nociforo,[1] R. Palit,[17] S. Paschalis,[4,7] R. Plag,[9,1] R. Reifarth,[9,1] D. Savran,[18,19] H. Scheit,[4] H. Simon,[1] K. Sümmerer,[1] A. Wagner,[11] W. Waluś,[12] H. Weick,[1] and M. Winkler[1]

R3B